Science of the Total Environment 665 (2019) 579–590

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Partitioning climate and human contributions to changes in mean annual streamflow based on the Budyko complementary relationship in the Loess Plateau, China

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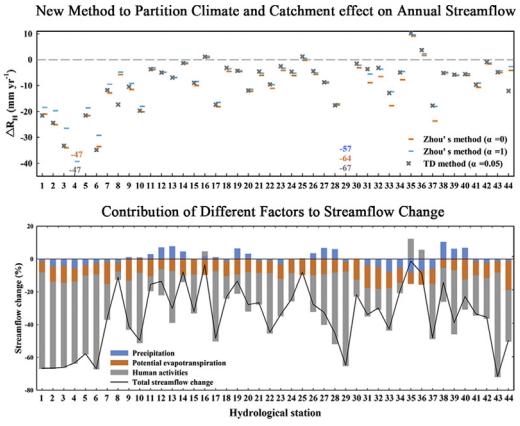
HIGHLIGHTS

- Annual streamflow significantly decreased by 36% on average after the GFG project.
- Half of the stations in estimating human effect are underestimated or overestimated by the total differential method.
- Potential evapotranspiration alone decreased streamflow by 9% (or 42% as relative value).

GRAPHICAL ABSTRACT


New Method to Partition Climate and Catchment effect on Annual Streamflow
Zhou' s method (α =0)
Zhou' s method (α =1)
TD method (α =0.05)
Contribution of Different Factors to Streamflow Change
Precipitation
Potential evapotranspiration
Human activities
Total streamflow change
Streamflow change (%)
Hydrological station

ARTICLE INFO

Article history:
Received 6 December 2018
Received in revised form 11 January 2019
Accepted 29 January 2019
Available online 30 January 2019

Editor: Ouyang Wei

Keywords:
Time-varying streamflow
Climate change
Human activity
Budyko-based complementary method
Loess Plateau

ABSTRACT

Reliable attribution of changes in streamflow is fundamental to our understanding of the hydrological cycle and is needed to enable decision makers to manage water resources in a sustainable way. Here, we used a new attribution method based on the Budyko framework (complementary method) to quantify the contributions of climate change and human activities to the changes in annual streamflow in 22 catchments on China's Loess Plateau during the past three decades. Our results showed that after the Grain-for-Green (GFG) project, the annual streamflow decreased by 36% on average (3–72%), with reductions being more intense in northern catchments. The sensitivity of streamflow to precipitation and potential evapotranspiration also decreased, with a mean rate of −0.7 mm yr^{-1}/mm yr^{-1} and −0.2 mm yr^{-1}/mm yr^{-1}, respectively. Using the upper and lower bounds of the human effects on streamflow from the complementary method as a reference, we found that these effects at half of the stations were under- or overestimated by the total differential method. The contribution analysis from the complementary method showed that although human activities decreased streamflow by 26% (or 54% as a relative value) on average, the contribution of potential evapotranspiration alone to the decrease in streamflow was 9% (42%), highlighting the important role of increasing atmospheric moisture demand in the water cycle. In addition, the 5-year incremental analysis showed that the impacts of climate and human activities on streamflow had strong spatiotemporal variability.

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https://doi.org/10.1016/j.scitotenv.2019.01.386
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1. Introduction

1.1. Drivers of streamflow change

Streams are a critical freshwater source throughout much of the world (Patterson et al., 2013), yet the availability, access, and utilization of their flow are affected by both climate change and human activities (Piao et al., 2010; Liang et al., 2015a; Hovenga et al., 2016). This has a direct impact on the livelihoods of many, particularly people in arid and semiarid regions (Ziervogel et al., 2010; Faramarzi et al., 2013). Climate change influences streamflow through changes in timing, quantity, precipitation, rates of evaporation and transpiration as well as the soil moisture content (Merritt et al., 2006). By contrast, human activities influence streamflow through large-scale infrastructure such as reservoirs (Graf, 1999; Patterson et al., 2013), water withdrawals (Weiskel et al., 2007; Li et al., 2016a), urbanization (Ahn and Merwade, 2014) and ecological restoration projects (Liang et al., 2015b), which also impact groundwater recharge and evapotranspiration (Claessens et al., 2006). In the face of strong warming and significant precipitation variation (Stocker et al., 2013), as well as intensive human activities, the realization of regional sustainability has posed new concerns for water resource management. In response to this challenge, one of the tasks for hydrologists is to identify the different roles of climate change and human activities in the changes in streamflow.

Researchers have recently measured the impacts of climate change and human activities on annual streamflow by applying process-based models or Budyko-based approaches (Wang and Alimohammadi, 2012; Tang et al., 2013; Bourgault et al., 2014; Yang et al., 2014a; Liang et al., 2015b; Wu et al., 2016). The former generally analyzes contributions of driving factors via physical process simulations built into hydrological models or land surface models. These physically based models explicitly represent the processes related to the role of controlling factors; however, the required complex numerical solutions limit the opportunities for broader applications of these models (Wang et al., 2013). In contrast, the method based on Budyko curves (Budyko, 1974), which consider both water (precipitation) and energy (potential evapotranspiration) constraints in hydrological processes over a long-term period in a succinct way, provides a simple but effective tool to estimate long-term evaporation(E) and streamflow (Q) and to evaluate their responses to climate change (Sivapalan et al., 2003). In this framework, the key step is to calculate the sensitivity coefficients of streamflow with respect to precipitation (P), potential evapotranspiration (E_0) and the catchment parameter (n) based on partial derivatives. Assuming that P is independent of E_0 and that both P and E_0 are independent of parameter n, the total differential of Q can be used to assess the change in the mean annual streamflow based on Budyko functions (Roderick and Farquhar, 2011).

$$dQ = \frac{\partial Q}{\partial P}dP + \frac{\partial Q}{\partial E_0}dE_0 + \frac{\partial Q}{\partial n}dn. \quad (1)$$

The three partial derivatives $\partial Q/\partial P$, $\partial Q/\partial E_0$, and $\partial Q/\partial n$ represent the sensitivity coefficients of Q with respect to P, E_0, and n, respectively.

However, Eq. (1) is the first-order Taylor approximation of the total differential. Yang et al. (2014b) evaluated the error in climatic contribution to runoff and concluded that the climatic contribution is underestimated as P increases or as E_0 decreases but is overestimated otherwise as a result of ignoring high-order terms in the Taylor series expansion. Recently, Zhou et al. (2016) proposed a new partition method based on the Budyko complementary relationship (complementary method hereinafter) for streamflow; this method has proven better than the total differential method in estimating the human activity effects, with the average range of the catchment effect being 6.7 mm and 51.5 mm, respectively, based on 14 catchments in Australia.

1.2. Previous studies attributing climate and human influences to streamflow in the Loess Plateau

The Loess Plateau, which is the main portion of the Yellow River, is an ecologically vulnerable region and is well known for its high soil erosion rates (Lü et al., 2012). To address pressing environmental problems and to improve ecosystem services, a series of national policies, such as the "Natural Forest Protection project" and the Grain-for-Green (GFG) project, were implemented. The GFG project was launched in 1999 and aims to increase forest cover and mitigate soil erosion by converting agricultural lands to forest and grasslands (Liu et al., 2008). This large-scale ecological restoration activity greatly alters the water balance of a catchment by increasing rainfall interception and actual evapotranspiration (Feng et al., 2012). Simultaneously, it has been reported that the plateau has been experiencing a clear drying trend. The combined effect has resulted in an obvious downward trend in the streamflow in this region (Zhao et al., 2014) and consequently, negative effects on local ecosystems (Wang et al., 2011).

Numerous studies have attempted to investigate the reason for the decrease in streamflow in the Loess Plateau. Li et al. (2009), using a process-based model, concluded that climate change and land use decreased streamflow by 95.8% and 9.6%, respectively, in a tributary of the Jinghe River, located on the Loess Plateau. In comparison, a study in the middle reaches of the Yellow River basin by Gao et al. (2011) found that a decrease of 28% in streamflow was attributed to precipitation based on the double mass curve method. Other studies based on the Budyko hydrological model have confirmed the dominant role of human activities in the decline of annual streamflow (Zhang et al., 2008; Zhao et al., 2014; Liang et al., 2015b; Wu et al., 2016). The above studies highlight how the relative contributions of climate- and human-induced changes to streamflow differ depending on the location. However, most of the previous efforts were limited by the low number of hydrological stations (an exception is Zhao et al. (2017)). The changing streamflow and its response to climate change and human activities on the whole plateau have not been fully documented. Due to changes in both climate and human activities over time (Patterson et al., 2013), an assessment of the effects of temporal variations in these factors on streamflow is needed to develop adaptive measures for regulating water yield to ensure water security in this region.

Therefore, the objectives of this study are to (1) investigate the changes in annual hydro-meteorological variables for the 22 catchments (or 44 sections) within the Loess Plateau; (2) characterize the streamflow sensitivity of these catchments; (3) validate the complementary method; and (4) partition the impacts of climate change and human activities on streamflow after the GFG project and for each 5-year increment.

2. Methods

The Budyko hypothesis (Budyko, 1974) stipulates that annual water balances can be expressed as a function of available water (P) and energy (E_0), expressed as

$$\frac{E}{P} = F\left(\frac{E_0}{P}\right). \quad (2)$$

A number of mathematical functions have been proposed to represent the Budyko hypothesis (Mezentsev, 1955; Fu, 1981; Choudhury, 1999; Zhang et al., 2001; Yang et al., 2008). A previous study by Zhou et al. (2015) showed that Mezentsev-Choudhury-Yang's function has a superior analytical form among the existing Budyko functions to describe the water-energy balance. Thus, this function was used in our study (Mezentsev, 1955; Choudhury, 1999; Yang et al., 2008).

$$\frac{E}{P} = \frac{E_0/P}{\left[1 + (E_0/P)^n\right]^{1/n}} \quad (3)$$

where n represents land surface characteristics of a given catchment, such as soil properties, slope, vegetation cover, and climate seasonality (Yang et al., 2008; Donohue et al., 2012; Zhang et al., 2018.

In long-term catchment water balance, the changes in soil water storage within a given catchment are negligible. Therefore, the mean annual streamflow can be regarded as the difference between P and E. Then, we can obtain:

$$Q = P - \frac{E_0 P}{\left[P^n + {E_0}^n\right]^{1/n}}. \quad (4)$$

To separate the contribution of streamflow from climate change and human activities, we adopted the method proposed by Zhou et al. (2016). This method (complementary method) is distinct from the total differential method in estimating human effects. Algebraic identities ensure that the change in the mean annual streamflow can be partitioned precisely into three components: the effect of precipitation (ΔQ_P), potential evapotranspiration (ΔQ_{E_0}) and human activities (ΔQ_H).

$$\Delta Q_p = \left[\alpha\left(\frac{\partial Q}{\partial P}\right)_1 + (1-\alpha)\left(\frac{\partial Q}{\partial P}\right)_2\right]\Delta P \quad (5)$$

$$\Delta Q_{E0} = \left[\alpha\left(\frac{\partial Q}{\partial E_0}\right)_1 + (1-\alpha)\left(\frac{\partial Q}{\partial E_0}\right)_2\right]\Delta E_0 \quad (6)$$

$$\Delta Q_H = \alpha\left[P_2\Delta\left(\frac{\partial Q}{\partial P}\right) + E_{0,2}\Delta\left(\frac{\partial Q}{\partial E_0}\right)\right] + (1-\alpha) \times \left[P_1\Delta\left(\frac{\partial Q}{\partial P}\right) + E_{0,1}\Delta\left(\frac{\partial Q}{\partial E_0}\right)\right]. \quad (7)$$

The numbers 1 and 2, presented as subscripts, represent the different periods. Parameter α is a weighting factor, and its value varies from 0 to 1.

Thus, the upper and lower bounds of ΔQ induced by these three factors are reached when the weighting factor α assumes extreme values of 0 or 1. More details of the complementary method can be found in Zhou et al. (2016).

3. Study area and data

3.1. Study area

The Loess Plateau (which lies approximately within 34°–41°N, 98°–114°E) covers an area of 632,520 km^2 and is located in the middle reaches of the Yellow River basin in northwestern China, accounting for 6.3% of the entire land area of China (Fig. 1). The long-term annual average precipitation is approximately 430 mm yr^{-1}; 60–70% of the annual precipitation occurs between June and September in the form of high-intensity rainstorms, which often cause extreme soil erosion, and drought frequently happens. The annual average temperature is 9.0 °C, with a minimum mean temperature of −4.6 °C in winter and a maximum mean temperature of 20.9 °C in summer (Yan et al., 2013).

Due to the thick and highly erodible loess, unevenly distributed precipitation, relatively high-intensity rainstorms, and intensive human activities, accelerated soil erosion occurs in the study region (Xu, 2011). In 1999, to mitigate soil erosion and to increase forest cover, the Chinese government launched the GFG project, mainly in areas where slopes exceed 15°. This project significantly increased the tree cover of the plateau and thus altered the regional climate and hydrological processes (Xiao, 2014; Li et al., 2016a).

Based on the available hydrological datasets from 1980 to 2009, 22 catchments (44hydrological stations) located across strong climate and land surface gradients were selected for this study (see Fig. 1). The drainage areas of the study catchments range from 283 to 106,498 km^2, and the aridity index (E_0/P) spans a range of 1.6 to 3.2. Details of the long-term hydro-meteorological variables of these catchments are listed in Table 1. Note that for the sections between two hydrological stations, the streamflow depth (mm) is the total volume of streamflow (m^3) divided by the controlled area between these stations.

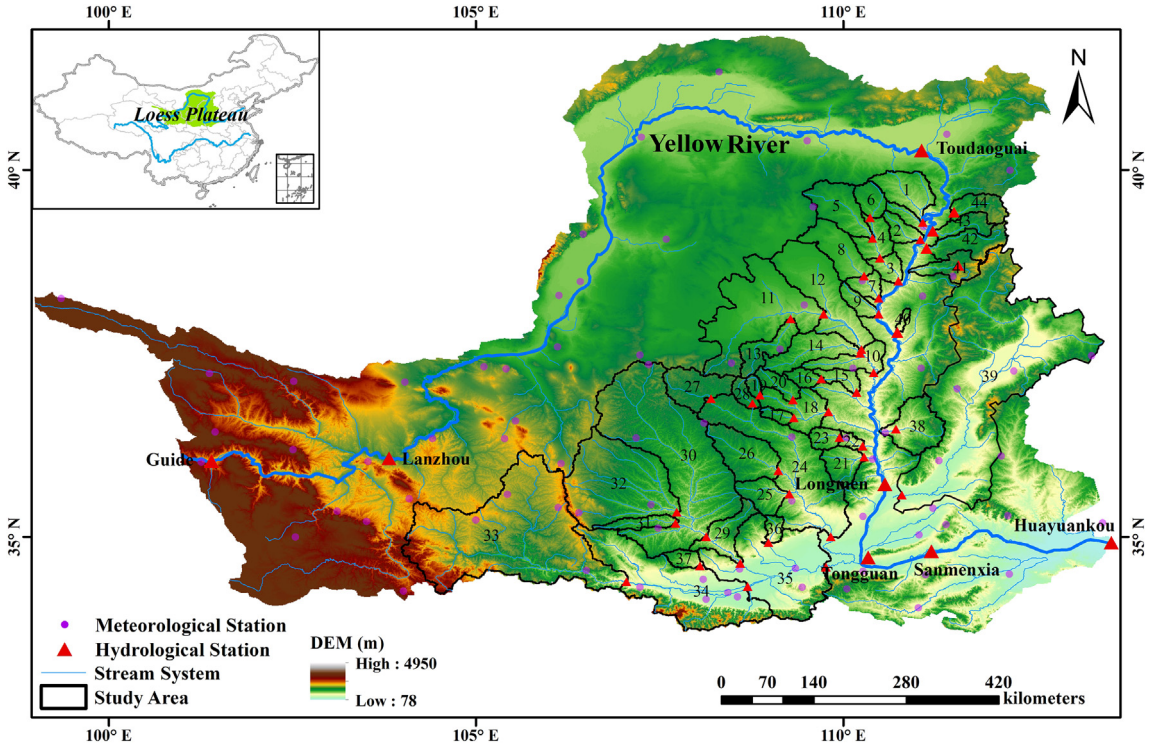

Fig. 1. Location for the study area within the Loess Plateau. The red triangles represent 44 hydrological stations, and the purple circles represent 79 meteorological stations.

3.2. Data

Annual streamflow data from 1980 to 2009 for the 44 hydrological stations were acquired from the Yellow River Conservancy Commission. Daily meteorological variables, including precipitation, air temperature, sunshine duration, wind speed, and relative humidity, for the period 1980–2009 were provided by the National Climatic Center of the China Meteorological Administration (http://cdc.nmic.cn/). Potential evaporation was estimated using the Penman method (Penman, 1948). The Angstrom-Prescott formula (Prescott, 1940) was used to convert sunshine hours into energy units to calculate solar radiation (McVicar et al., 2007). Semi-empirical coefficients a and b in this formula at ten stations near our study region with radiation observations were obtained from Wang et al. (2012). All the meteorological data were spatially averaged across the study area by the coKriging interpolation algorithm, with a spatial resolution of 1 km.

The afforestation area of each county including returning cropland to forest, afforestation of barren land, and mountain closure (e.g., prohibition of fuelwood collection and grazing) from 2000 to 2009 was obtained from the Forestry Department of Shaanxi Province. The crop yield of each county in Shaanxi Province was obtained from the National Earth System Science Data Sharing Infrastructure (http://www.geodata.cn/).

4. Results

4.1. Changes in annual hydro-meteorological variables

As shown in Table 2, annual streamflow showed a decreasing trend at all stations except the Kelan station during the period 1980–2009, with an average rate of −1.0 mm per year for 43 stations (ranging from −0.1 to −4.7 mm yr^{-2}). Twenty-six stations experienced a significant decreasing trend, which was distributed mainly on the right bank of the Yellow River. In contrast, the mean annual precipitation at 31 stations exhibited negative trends, with rates ranging from −0.1 to −3.6 mm yr^{-2} (−1.6 mm yr^{-2} on average). The 13other stations revealed the opposite trend of 0.3 mm yr^{-2} (ranging from 0.1 to 0.4 mm yr^{-2}). However, no statistically significant trends in annual precipitation at any of these stations were identified. For annual potential evapotranspiration, all stations presented positive trends, with rates of increase ranging from 2.3 to 6.4 mm yr^{-2} (4.2 mm yr^{-2} on average).

Table 1
Basic catchment characteristics and long-term (1980–2009) annual mean precipitation (P), potential evapotranspiration (E_0), streamflow (Q), and dryness index (E_0/P) of the 22 catchments (44 stations) shown in Fig. 1. The unit of P, E_0 and Q is mm yr^{-1}.

Catchment	ID	Hydrological station	Area (km^2)	Lon	Lat	Long-term annual mean value (1980–2009)			
						P	E_0	Q	E_0/P
Huangfuchuan	1	Huangfu	3175	111°05′	39°17′	383.8	1013.2	26.1	2.7
Gushanchuan	2	Gaoshiya	1263	111° 03′	39°03′	393.3	1022.3	33.0	2.7
Kuye River	3	Wenjiachuan	8515	110°45′	38°29′	412.1	1064.4	45.8	2.7
	4	Shenmu	7298	110°30′	38°48′	393.4	1051.8	68.4	2.8
	5	Wangdaohengta	3839	110°24′	39°04′	366.4	1105.9	33.8	3.1
	6	Xinmiao	1527	110°22′	39°21′	380.6	1060.0	42.2	2.9
Tuwei River	7	Gaojiachuan	3253	110°29′	38°15′	410.1	1082.6	44.9	2.7
	8	Gaojiabao	2095	110°17′	38°33′	379.0	1098.1	103.6	3.0
Jialu River	9	Shenjiawan	1121	110°29′	38°02′	410.6	1094.3	30.0	2.8
Wuding River	10	Baijiachuan	29,662	110°25′	37°14′	437.0	1088.2	37.1	2.6
	11	Dingjiagou	23,422	110°15′	37°33′	386.4	1120.0	36.9	3.0
	12	Zhaoshiyao	15,253	109°44′	38°02′	364.8	1139.9	29.8	3.2
Lu River	13	Hengshan	2415	109°17′	37°58′	396.2	1098.3	19.7	2.9
Dali River	14	Suide	3893	110°14′	37°30′	420.6	1093.5	32.7	2.7
Qingjian River	15	Yanchuan	3468	110°11′	36°58′	448.6	1052.4	34.9	2.4
	16	Zichang	913	109°42′	37°09′	443.3	1045.1	41.3	2.4
Yan River	17	Zaoyuan	719	109°20′	36°38′	472.7	992.6	34.2	2.2
	18	Ganguyi	5891	109°48′	36°42′	468.4	997.4	26.5	2.2
	19	Xinghe	479	108°52′	36°56′	429.8	1018.5	36.1	2.5
	20	Ansai	1334	109°19′	36°52′	437.0	1033.5	44.8	2.5
Shiwang River	21	Dacun	2141	110°17′	36°05′	522.7	986.0	26.4	2.0
Fenchuan River	22	Xinshihe	1662	110°16′	36°14′	499.3	968.6	23.9	2.0
	23	Linzhen	1121	109°57′	36°21′	502.2	975.1	14.6	2.0
Beiluo River	24	Zhuangtou	25,645	109°50′	35°00′	517.0	986.8	30.6	2.0
	25	Huangling	2266	109°16′	35°35′	542.9	964.9	46.2	1.9
	26	Zhangcunyi	4715	109°07′	35°54′	502.6	949.5	22.0	2.0
	27	Wuqi	3408	108°12′	36°53′	397.5	1022.3	25.4	2.7
	28	Zhidan	774	108°46′	36°49′	432.2	999.8	33.5	2.4
Jing River	29	Zhangjiashan	43,216	108°36′	34°38′	558.0	920.4	83.1	1.7
	30	Jingcun	40,281	108°08′	35°00′	462.8	960.1	23.6	2.2
	31	Zhanghe	1506	107°43′	35°11′	536.8	840.8	37.1	1.6
	32	Yangjiaping	14,124	107° 4′	35°20′	486.8	889.4	36.4	1.9
Wei River	33	Linjiacun	30,661	107°03′	34°23′	488.3	788.7	50.4	1.7
	34	Xianyang	46,827	108°42′	34°19′	571.3	839.7	96.0	1.6
	35	Huaxian	106,498	109°46′	34°35′	571.0	948.7	76.2	1.8
	36	Yaoxian	797	108°59′	34°55′	554.7	1009.6	34.7	1.9
	37	Antou	1007	108°03′	34°36′	567.4	853.3	52.0	1.6
Xinshui River	38	Daning	3992	110°43′	36°28′	481.1	998.0	23.4	2.2
Fen River	39	Hejin	38,728	110°48′	35°34′	473.6	996.1	13.2	2.2
Qingliangsigou	40	Yangjiapo	283	110°44 ′	37°47′	434.7	1084.4	29.3	2.6
Dongchuan River	41	Kelan	476	111°34′	38°42′	432.7	1007.2	35.9	2.4
Zhujiachuan	42	Qiaotou	2854	111°13′	38°56′	425.7	988.7	5.2	2.4
Xianchuan River	43	Jiuxian	1562	111°13′	39°10′	414.5	973.2	5.5	2.4
Pianguan River	44	Pianguan	1896	111°29′	39°26′	409.8	963.9	8.6	2.4

Table 2
Trends of annual Q, P, E_0 for the 44 stations from 1980 to 2009 by using the linear regression method, and their changes from period-1 (1980–1999) to period-2 (2000–2009), expressed as a percentage (%).

ID	Station	Trends (mm yr-2)			Changes from period 1 to period 2		
		Q	P	E_0	Q	P	E_0
1	Huangfu	−1.3**	0.4	3.5**	−67	−1	6
2	Gaoshiya	−1.3**	−0.1	5.0***	−67	−3	9
3	Wenjiachuan	−2.4***	−0.3	6.3***	−66	−3	11
4	Shenmu	−1.8*	−0.3	5.9***	−64	−4	11
5	Wangdaohengta	−1.5***	0.4	3.6*	−58	−2	6
6	Xinmiao	−2.1***	0.4	4.0**	−67	−2	7
7	Gaojiachuan	−0.8	−0.1	6.4***	−37	−1	11
8	Gaojiabao	−1.6***	0.1	5.1**	−23	−2	9
9	Shenjiawan	−0.8***	0.1	6.1**	−42	1	11
10	Baijiachuan	−1.1*	−0.9	4.8**	−50	1	7
11	Dingjiagou	−0.3	0.2	4.7*	−17	1	8
12	Zhaoshiyao	−0.3***	0.4	2.7	−15	3	4
13	Hengshan	−0.4***	−0.1	3.2	−31	3	5
14	Suide	−0.1	−0.6	4.1*	−9	2	7
15	Yanchuan	−0.3	−1.5	4.5**	−33	0	7
16	Zichang	−0.1	−1.4	4.1*	−5	1	6
17	Zaoyuan	−0.8*	−1.8	4.3**	−49	1	6
18	Ganguyi	−0.6*	−2.2	4.3**	−30	−1	6
19	Xinghe	−0.3	−0.6	4.2*	−15	3	6
20	Ansai	−0.3	−1.1	4.0*	−29	1	6
21	Dacun	−0.9**	−2.1	3.3	−28	−1	5
22	Xinshihe	−0.8*	−2.3	3.6*	−45	−1	6
23	Linzhen	−0.4***	−2.7	4.1*	−35	−1	6
24	Zhuangtou	−0.7***	−2.0	4.0*	−26	0	6
25	Huangling	−0.8	−2.3	4.4*	−9	0	6
26	Zhangcunyi	−0.5**	−1.5	4.6**	−29	1	7
27	Wuqi	−0.3	0.3	4.4**	−34	3	7
28	Zhidan	−0.8*	−0.5	4.3**	−46	3	7
29	Zhangjiashan	−4.7***	−2.9	4.2*	−65	−1	6
30	Jingcun	−0.3	−1.2	5.0**	−23	0	8
31	Zhanghe	−1.2**	−2.6	5.1**	−35	−2	10
32	Yangjiaping	−0.9***	−1.9	5.0***	−31	−2	10
33	Linjiacun	−2.2***	−2.1	3.8**	−44	−4	8
34	Xianyang	−3.1*	−3.2	4.1*	−21	−3	7
35	Huaxian	−1.2	−3.5	3.4	−3	−3	5
36	Yaoxian	−0.8	−3.2	4.0*	−10	−3	5
37	Antou	−2.5***	−3.6	4.2*	−49	−3	7
38	Daning	−0.3**	−0.4	2.3	−16	4	3
39	Hejin	−0.3	−0.4	3.5*	−40	3	5
40	Yangjiapo	−0.1	0.2	5.4**	−24	3	9
41	Kelan	0.2	0.1	3.7**	−34	−1	6
42	Qiaotou	−0.1	0.2	3.4*	−36	−1	6
43	Jiuxian	−0.2	0.3	3.1*	−72	−1	6
44	Pianguan	−0.4	0.4	2.3	−65	0	4

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$. Trends with no asterisk are not significant (>0.05).

To investigate the changes in streamflow before and after the GFG project, the entire study period was split into two parts: period 1 (1980–1999) and period 2 (2000–2009). The annual streamflow at all stations decreased, varying from −3% at the Huaxian station to −72% at the Jiuxian station (−36% on average). By comparison, the rate of change of both annual precipitation and potential evapotranspiration at most stations was <10%, indicating that climate change was not the dominant factor responsible for the decline in the streamflow, which is consistent with previous studies on the Loess Plateau (Liang et al., 2015b; Gao et al., 2017).

4.2. Parameter n and streamflow sensitivity

Parameter n, which represents the catchment characteristics, was estimated by Eq. (3). For a given precipitation and potential evapotranspiration, a higher n indicates higher actual evapotranspiration and lower streamflow (Patterson et al., 2013). As shown in Fig. 2, the value of n showed a large spatial variation, with a mean value of 2.3, ranging from 0.9 at the Gaojiabao station to 3.7 at the Qiaotou station. After the GFG project, the forest area greatly increased at the cost of decreased cropland area (Fig. S1). However, crop yield from the Wuding River basin (a basin in the middle of the Loess Plateau) increased by 153% from 1990 to 2010 (Liang et al., 2015b). Therefore, we explored the impacts of afforestation and crop yield on parameter n. Note that due to the lack of information on the afforestation area in Shanxi and Gansu provinces, here we only focused on the hydrological stations of Shaanxi province. As shown in Fig. 3a, the ratio of the total afforestation area tended to be significantly correlated with parameter n ($R = 0.63$, $p < 0.01$). In contrast, an insignificant correlation of crop yield with parameter n can be observed in Fig. 3b.

Analysis of the streamflow sensitivity indicates that the higher the value of parameter n, the less sensitive streamflow is to precipitation and potential evapotranspiration (Fig. 2 and Fig. 4), indicating that the river system of drylands is less sensitive to climate change in terms of water yield. The mean $\partial Q/\partial P$ and $\partial Q/\partial E_0$ values are 0.23 mm yr^{-1}/mm yr^{-1} and -0.07 mm yr^{-1}/mm yr^{-1}, respectively, suggesting that there is an approximate 2.3 mm yr^{-1} increase in streamflow for every 10 mm yr^{-1} increase in precipitation and a 0.7 mm yr^{-1} decrease in streamflow for every 10 mm yr^{-1} increase in potential evapotranspiration. To preliminarily explore the reason for the streamflow decrease, we analyzed the changes in $\partial Q/\partial P$ and $\partial Q/\partial E_0$ before and after the year 2000 (Table 3). The results showed that both $\partial Q/\partial P$ and $\partial Q/\partial E_0$ decreased at all stations, with a mean rate of −0.7 mm yr^{-1}/mm yr^{-1} (ranging from −0.1 to −2.0 mm yr^{-1}/mm yr^{-1}) and − 0.2 mm yr^{-1}/mm yr^{-1} (ranging from −0.04 to −0.6 mm yr^{-1}/mm yr^{-1}), respectively.

4.3. Validation of the complementary method

In the complementary method, the estimated streamflow change (ΔQ) is always equal to the observed value (i.e., the streamflow difference between two periods). Thus, we first compared the complementary method (also regarded as the observation) with the total differential (TD) method in the estimation of ΔQ. As Fig. 5a shows, the modeled streamflow change varied with the value of α based on the TD method. If $\alpha = 0.5$, the mean bias of the modeled ΔQ for the 44 stations was 3.1%, indicating that the TD method slightly overestimated ΔQ. However, these differences were large when α equaled 0 or 1, especially for the Zhangjiashan and Shenmu stations. The mean bias of the modeled ΔQ was 30% when $\alpha = 0$ and − 18% when $\alpha = 1$.

In terms of changes in streamflow induced by human activities (ΔQ_H), these two methods were highly consistent, with a coefficient of determination (R^2) of 0.96 when $\alpha = 0.5$ (Fig. 5b). Nevertheless, the uncertainty of ΔQ_H from the complementary method was much

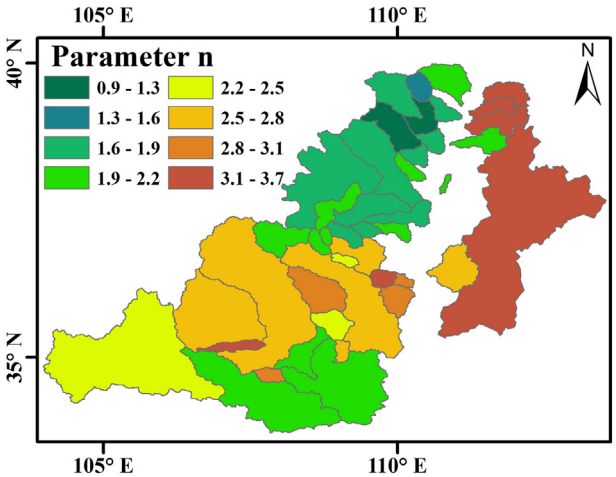

Fig. 2. The parameter n (catchment characteristics) of the study catchments.

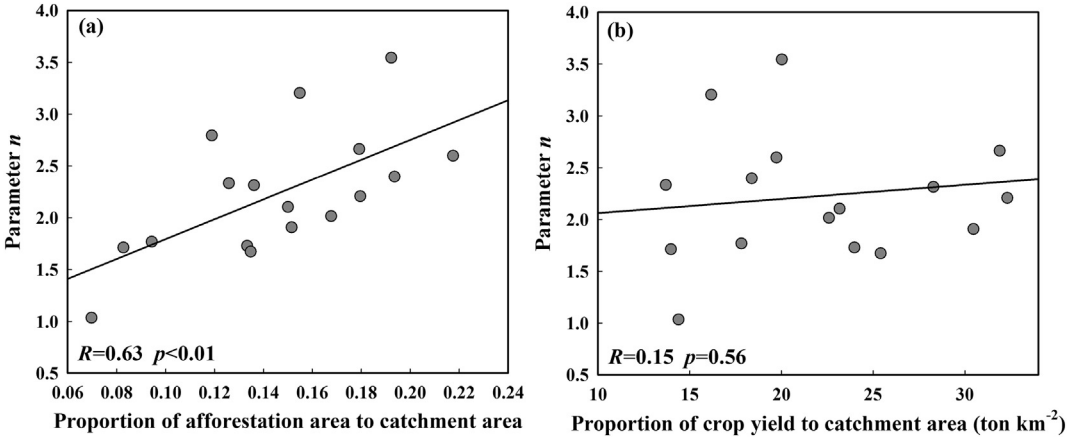

Fig. 3. Relationship of parameter n with: (a) the ratio of total afforestation area to the region, and (b) the ratio of crop yield to the region between the hydrological stations from 2000 to 2009.

lower than that from the TD method when α ranged from 0 to 1. The range of ΔQ_H was only 2 ± 2.1 mm yr^{-1} with the complementary method (accounting for 5% of the annual mean streamflow of all stations). In contrast, the range of ΔQ_H was 8.2 ± 13.6 mm yr^{-1} based on the TD method (24%). For some stations, such as Jiuxian and Pianguan, this value exceeded 95%.

Fig. 5c shows the comparison of the upper and lower bounds with the estimated ΔQ_H using the complementary method and the TD method ($\alpha = 0.5$). The results suggested that ΔQ_H across 21 stations estimated from the TD method was within the range estimated from the complementary method. In comparison, fifteen and eight stations had higher and lower values than the respective upper and lower bounds of ΔQ_H from the complementary method, indicating that ΔQ_H may be underestimated and overestimated, respectively, by the TD method. These findings therefore indicate that the complementary method can precisely evaluate the impact of climate change and human activities on streamflow change, especially the latter in terms of magnitude.

4.4. Impacts of climate change and human activities on streamflow

Based on the above analysis and the complementary method, we estimated the streamflow change induced by climate (Eqs. (5) and (6)) and human drivers (Eq. (7)), with α being 0.5.

4.4.1. Streamflow changes after the GFG project

As shown in Fig. 6, all stations experienced a consistent decrease in streamflow driven by potential evapotranspiration (−9% on average), while human activity contributions to streamflow further decreased streamflow at 40 stations (−29% on average) and increased streamflow at the four remaining stations (Huangling, Zichang, Yaoxian and Huaxian). In contrast, precipitation had a mixed effect on the streamflow, with 16 stations partly mitigating and 28 stations aggravating the decrease resulting from potential evapotranspiration and human activities (Fig. 6). For stations with streamflow induced by increasing precipitation (ΔQ_P), the mean contribution was 5% of the mean annual streamflow, while the contribution was only −3% with decreasing ΔQ_P.

4.4.2. Streamflow changes for each 5-year increment

Table 4 illustrates the temporal variation of streamflow change analysis. From the changes in streamflow induced by climate change ($\Delta Q_C = \Delta Q_P + \Delta Q_{E_0}$), one can see that a drier climate was prevalent in the middle and southern parts of the Loess Plateau throughout the period of 1985–2009 compared with that of 1980–1984. In comparison, ΔQ_C in some stations over the northern parts witnessed wetter climate conditions in the mid-1980s and early 1990s. In contrast, in terms of ΔQ_C, it was shown that stations on the middle part generally had a pattern opposite to that of ΔQ_C throughout the entire study period (i.e., climate decreased streamflow and human activity increased streamflow). For stations on the northern plateau, such as Huangfu, Gaoshiya, Wenjiachuan, Shenmu, Qiaotou, and Jiuxian, climate contributed to decreased streamflow, and human factors amplified this effect during the last 10 years. Furthermore, we found that human-induced changes in streamflow had greater variability than those induced by climate, with a mean standard deviation of 28% (ranging from 4% to 86%) and 17% (ranging from 4% to 35%), respectively.

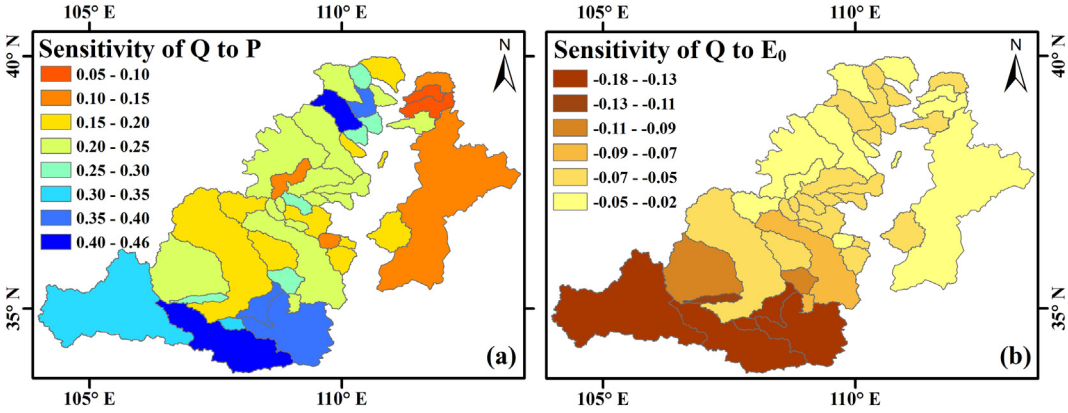

Fig. 4. Spatial pattern for (a) sensitivity of streamflow (Q) to changes in precipitation (P), and (b) in potential evapotranspiration (E_0).

Table 3
Changes in sensitivity of Q to P and E_0 from period-1 to period-2 for the 44 stations.

ID	Station	Sensitivity of Q to P (mm/10 mm)			Sensitivity of Q to E_0 (mm/10 mm)		
		Period-1	Period-2	Changes	Period-1	Period-2	Changes
1	Huangfu	2.3	1	−1.3	−0.5	−0.2	0.3
2	Gaoshiya	2.6	1.2	−1.4	−0.6	−0.3	0.3
3	Wenjiachuan	3.2	1.4	−1.8	−0.7	−0.3	0.3
4	Shenmu	4.1	2.1	−2.0	−0.7	−0.4	0.3
5	Wangdaohengta	2.6	1.4	−1.2	−0.5	−0.3	0.2
6	Xinmiao	3.1	1.4	−1.7	−0.6	−0.3	0.3
7	Gaojiachuan	2.9	2	−0.9	−0.6	−0.4	0.2
8	Gaojiabao	4.9	4.1	−0.8	−0.6	−0.5	0.1
9	Shenjiawan	2.2	1.4	−0.8	−0.5	−0.3	0.2
10	Baijiachuan	2.6	1.5	−1.1	−0.6	−0.4	0.2
11	Dingjiagou	2.4	2.1	−0.3	−0.5	−0.4	0.1
12	Zhaoshiyao	2.1	1.8	−0.3	−0.4	−0.3	0.0
13	Hengshan	1.6	1.2	−0.4	−0.4	−0.3	0.1
14	Suide	2.1	1.9	−0.2	−0.5	−0.4	0.1
15	Yanchuan	2.4	1.7	−0.7	−0.6	−0.4	0.2
16	Zichang	2.5	2.4	−0.1	−0.6	−0.6	0.1
17	Zaoyuan	2.5	1.5	−1.0	−0.7	−0.5	0.3
18	Ganguyi	1.9	1.5	−0.4	−0.6	−0.5	0.2
19	Xinghe	2.4	2.1	−0.3	−0.6	−0.5	0.1
20	Ansai	2.8	2.2	−0.6	−0.7	−0.5	0.1
21	Dacun	2	1.5	−0.5	−0.7	−0.6	0.2
22	Xinshihe	1.9	1.2	−0.7	−0.7	−0.4	0.3
23	Linzhen	1.3	0.9	−0.4	−0.5	−0.3	0.2
24	Zhuangtou	2.2	1.7	−0.5	−0.8	−0.6	0.2
25	Huangling	2.7	2.5	−0.2	−1.0	−0.9	0.1
26	Zhangcunyi	1.8	1.4	−0.4	−0.7	−0.5	0.2
27	Wuqi	2	1.4	−0.6	−0.5	−0.3	0.1
28	Zhidan	2.5	1.6	−0.9	−0.6	−0.4	0.2
29	Zhangjiashan	4.4	2.3	−2.1	−1.5	−0.9	0.6
30	Jingcun	1.9	1.5	−0.4	−0.6	−0.5	0.2
31	Zhanghe	2.8	2	−0.8	−1.3	−0.9	0.5
32	Yangjiaping	2.6	2	−0.6	−1.0	−0.7	0.3
33	Linjiacun	3.5	2.4	−1.1	−1.4	−0.9	0.5
34	Xianyang	4.5	3.9	−0.6	−1.9	−1.5	0.4
35	Huaxian	3.6	3.5	−0.1	−1.4	−1.2	0.2
36	Yaoxian	2.2	2	−0.2	−0.9	−0.7	0.1
37	Antou	3.5	2.2	−1.3	−1.6	−1.0	0.6
38	Daning	1.7	1.5	−0.2	−0.6	−0.5	0.1
39	Hejin	1.3	0.8	−0.5	−0.4	−0.3	0.1
40	Yangjiapo	2.1	1.6	−0.5	−0.5	−0.4	0.1
41	Kelan	2.5	1.8	−0.7	−0.6	−0.5	0.2
42	Qiaotou	0.6	0.4	−0.2	−0.2	−0.1	0.1
43	Jiuxian	0.7	0.3	−0.4	−0.2	−0.1	0.2
44	Pianguan	1.7	0.8	−0.9	−0.4	−0.2	0.2

5. Discussion

In light of the complexity of interactions between climate, hydrological processes, and catchment characteristics, such as soil and vegetation, streamflow is predisposed to exhibit nonlinear relationships with precipitation and potential evapotranspiration (Liu and Mcvicar, 2012; Patterson et al., 2013; Li et al., 2016b). The Loess Plateau has wide-ranging environmental conditions, and as a result, climatic and land surface conditions vary extensively (Liang et al., 2015a). During the last 30 years, annual streamflow at most of the stations (43 of 44) on the Loess Plateau experienced a negative trend (Table 2), which is consistent with previous findings in this region using the non-parametric Mann-Kendall test (Zhang et al., 2008; Liang et al., 2015b; Zhao et al., 2017). However, our analysis shows that the rate of change before and after the GFG project differed greatly for individual catchments, with northern catchments decreasing more strongly. In addition, parameter n and corresponding sensitivity of streamflow to changes in climatic conditions varied from catchment to catchment (Figs. 2 and 4). The results highlight the importance of analyzing streamflow and its driving factors at the individual catchment level, and these driving factors were not fully understood in previous studies.

The reliable attribution of changes in streamflow is fundamental to our understanding of the hydrological cycle and is needed to enable decision makers to manage water resources in a sustainable way (Huntington, 2006). Generally, the streamflow of a catchment is a consequence of climate change and anthropogenic changes in water withdrawal and land use (Haddeland et al., 2014). However, it is almost impossible to directly separate the impacts of these factors (Tomer and Schilling, 2009). By using the elasticity/sensitivity method based on the Budyko framework, many scholars have conducted a contribution analysis of the long-term changes in annual or seasonal streamflow on the Loess Plateau, which are reported as relative figures rather than absolute values. For example, studies from the Wuding River Basin suggested that ecological restoration measures accounted for 65–87% of the total reduction in mean annual streamflow (Li et al., 2007; Liang et al., 2015b). A study on the Wei River by Zhan et al. (2014) stated that approximately 22–29% of the streamflow decrease was due to climate change. However, another discussion by Jiang et al. (2015) showed that climate change was the main driving factor responsible for the decline in streamflow. Zhao et al. (2014) found that climate exerted a greater effect on the streamflow reduction in the Yan River (56%), while human activities accounted for more of the streamflow changes in other tributaries (77% on average), similar to the result presented by Liang et al. (2015a). More recently, Wu et al. (2016) concluded that human activities dominated streamflow reduction during the high-flow season (73%), which was opposite to the low-flow season.

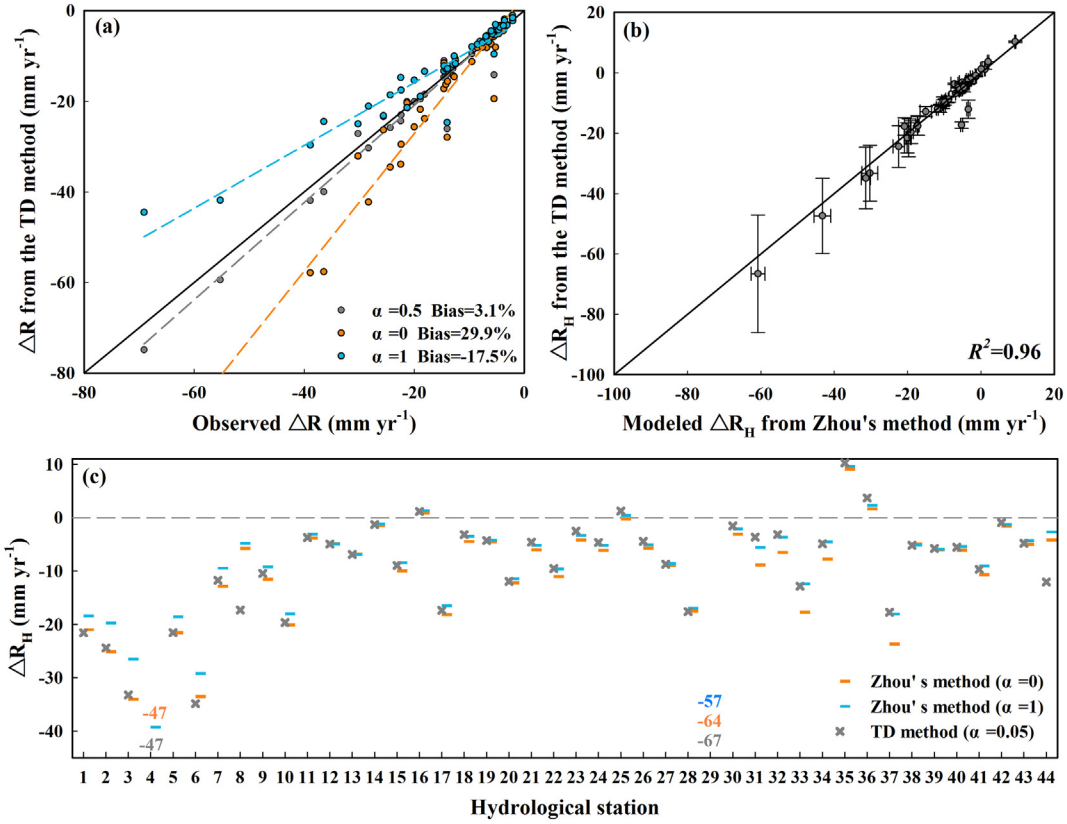

Fig. 5. Validation of the complementary method. (a) Comparison of the estimated $\triangle Q$ using the complementary method (observed $\triangle Q$) and using the total differential (TD) method; (b) comparison of the $\triangle Q_H$ between the complementary method (Zhou's method) and the TD method with α being 0.5. The error bars show the range of the estimated $\triangle Q_H$ when α varies from 0 to 1; and (c) comparison of the $\triangle Q_H$ using the TD method and the upper and lower bounds using the complementary method.

Nevertheless, the sensitivity coefficients in most studies were estimated using the long-term mean annual data over the whole period (an exception is Jiang et al. (2015), which could result in large discrepancies in the estimated $\triangle Q$ (Zhou et al., 2016).

At the end of the 20th century, the Chinese government launched the GFG project, which substantially altered the land cover of the Loess Plateau. In this study, we adopted the complementary method, proposed by Zhou et al. (2016), to partition climate and human effects on the annual streamflow of 22 catchments during the past three decades. Our analysis showed that the human effect on half of the catchments was underestimated or overestimated by the original sensitivity method ($\alpha = 0.5$) (Fig. 5c). In terms of the climate effect, precipitation and potential evapotranspiration, representing available water and energy, respectively, are two key climate variables that influence hydrological processes (Budyko, 1974). These variables can lead to changes in streamflow directly or indirectly. The result from the complementary method revealed that precipitation has both positive and negative effects on streamflow, with the latter being primarily distributed in the northern catchments and the Wei River (Fig. 6). In contrast, potential evapotranspiration decreased streamflow by 9% on average

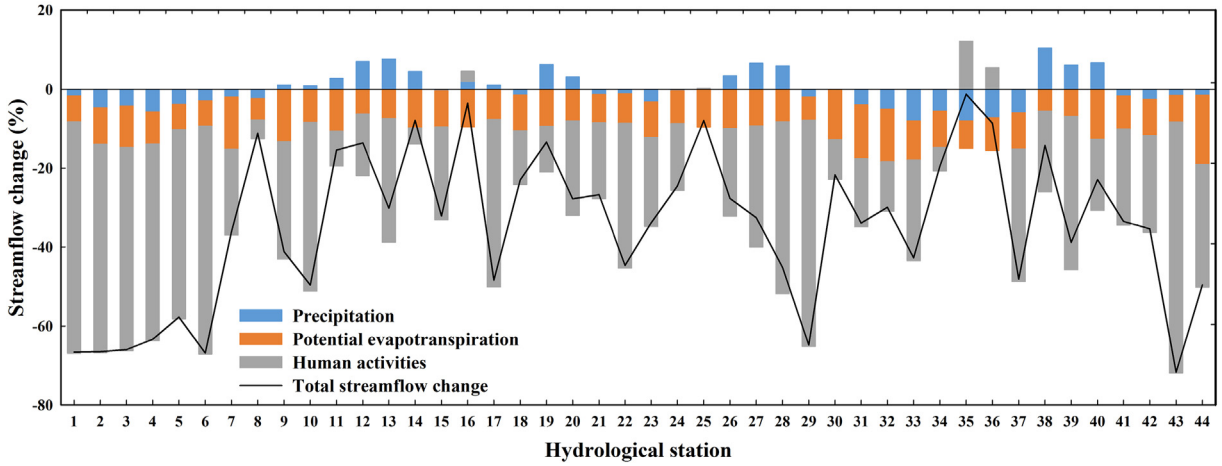

Fig. 6. Contribution of P, E_0, and human impacts to the total change in streamflow.

(42% based on a relative value), highlighting the importance of increasing atmospheric moisture demand in the water cycle, despite these climate effects ($\Delta Q_P + \Delta Q_{E_0}$) being predominantly outweighed by the impact of humans, which is mainly related to the afforestation activities in our study area.

Afforestation has been implemented worldwide as regional and national policies to sequester carbon, control soil erosion or restore other ecosystem services (Bonan, 2008; Liu et al., 2008; Pan et al., 2011). The tree cover of the Loess Plateau resulting from the GFG project greatly increased, with a relative increase of 41% (Xiao, 2014). This conversion of croplands to forestlands can influence rooting characteristics, leaf area, surface albedo, and turbulence (Jackson et al., 2001; Farley et al., 2005; Li et al., 2015), all of which will tend to increase evapotranspiration and thus lower streamflow. This is partly confirmed by the correlation analysis between parameter *n* in the Budyko framework and the afforestation area (Fig. 3). In general, climate change and human activities decreased annual streamflow by an average of 9% (46% as a relative value) and 26% (54%) for the 44 catchments (Fig. 6). In addition, the streamflow changes for each 5-year increment showed that climate and human effects have strong spatiotemporal variability (Table 4). For catchments located in the middle part of the plateau, these two effects are generally opposite throughout the entire study period. By comparison, the reduction of streamflow in northern catchments was caused by both climate change and human activities during the period 2000–2010. Moreover, our results showed that human-induced changes in streamflow have greater variability than those induced by climate (28% versus 17%) (Table 4).

In general, the increased evapotranspiration induced by large-scale ecological restoration projects is identified as the primary driver of the observed decline in streamflow. Nevertheless, there are still some uncertainties and limitations associated with quantifying the impacts of climate change and human activities on streamflow change in this study. First and foremost, attribution analysis in this study was based on the assumption that the hydrological responses to climate change (represented by precipitation and potential evapotranspiration) and human activities (represented by land surface parameter n) are independent. However, interactions exist between the two factors in natural catchments. For example, vegetation restoration modifies land surface

Table 4
Percentage change in streamflow induced by climate change (ΔQ_C) and human factors (ΔQ_H) from the baseline streamflow from 1980 to 1984 at 5-year intervals. Cell are color-scaled to represent the contribution rate (deeper color for higher rate). Red and blue colors represent decrease and increase in streamflow, respectively.

ID	Climate change (%)					Human activities (%)				
	85–89	90–94	95–99	00–04	05–09	85–89	90–94	95–99	00–04	05–09
1	3	15	2	−2	−5	−13	−46	−35	−61	−78
2	16	17	−1	−10	−10	25	14	−4	−46	−56
3	23	15	−5	−8	−8	7	−25	−56	−79	−44
4	17	15	2	−12	−11	16	25	69	−26	−52
5	22	21	12	4	−2	−16	−35	−51	−66	−63
6	12	17	7	0	−4	−10	−32	−47	−60	−80
7	34	30	−10	−7	−8	22	39	4	−22	1
8	13	12	2	0	−1	−2	−3	0	0	−10
9	29	30	−14	−1	−3	−46	−24	−3	−42	−45
10	19	15	−44	−6	−16	42	−20	26	−56	−13
11	26	30	−13	6	0	−37	−35	22	−12	−31
12	29	33	−9	25	2	−25	−39	−3	−38	−25
13	10	24	−29	14	−13	−14	−14	4	−50	−20
14	7	19	−48	−4	−17	−1	6	53	10	9
15	−4	4	−84	−20	−36	45	100	132	25	30
16	−15	−1	−82	−22	−36	44	35	118	80	15
17	−37	−35	−91	−26	−47	97	120	102	12	3
18	−32	−18	−80	−28	−50	51	−20	56	5	6
19	−3	8	−46	5	−29	−6	19	41	−3	4

(*continued on next page*)

Table 4 (*continued*)

20	−12	0	−73	−10	−39	42	142	109	33	32
21	−33	−31	−55	−29	−44	13	−14	−10	−21	−9
22	−41	−39	−71	−33	−44	60	62	28	0	−13
23	−38	−36	−77	−34	−56	20	11	30	−17	8
24	−36	−40	−68	−33	−47	38	26	31	15	−4
25	−33	−44	−64	−39	−49	0	9	7	11	2
26	−27	−34	−70	−24	−46	22	36	39	0	1
27	26	39	−12	30	−15	13	68	42	−17	−6
28	−3	7	−48	6	−25	25	37	51	−19	−35
29	−36	−46	−58	−36	−32	1	18	−4	−34	−50
30	−13	−12	−53	−13	−47	21	13	45	−1	16
31	−34	−39	−63	−37	−56	13	13	7	−10	1
32	−14	−11	−47	−18	−48	−10	−10	11	−19	−5
33	−10	−10	−32	−22	−34	−12	−19	−39	−43	−22
34	−37	−40	−47	−41	−45	−6	−7	−33	−22	−1
35	−45	−46	−65	−56	−50	11	−14	6	17	9
36	−39	−51	−67	−56	−50	−11	−7	6	21	−11
37	−47	−47	−64	−47	−48	15	−2	−6	−19	−22
38	−5	−6	−48	−4	−14	−8	12	22	−3	−24
39	13	−8	−47	−6	−14	1	−24	42	−42	−25
40	45	30	−23	9	2	−34	5	57	−32	3
41	24	28	−1	4	−4	−36	−10	176	−15	6
42	16	24	−1	0	−5	−45	−46	76	−26	−34
43	8	20	−1	−1	−4	−61	−64	50	−62	−84
44	14	54	−4	0	−16	19	3	72	16	35

conditions, then consequently alters surface evapotranspiration and its return as atmospheric precipitation (Li et al., 2017). Meanwhile, other factors such as climate seasonality can also change land surface properties (Milly, 1994; Roderick and Farquhar, 2011; Ning et al., 2017), which is confounded with human effects.

Second, an additional assumption was that any transient changes in water storage can be negligible (Li et al., 2007). Therefore, the attribution analysis was conducted at long-term scale, according to the steady state water balance of Budyko framework. It is not appropriate for attributing streamflow changes during a short-term or when the soil water storage changes largely (Zhang et al., 2018). Moreover, climate-induced streamflow change can be either underestimated or overestimated due to the changes of water storage between period 1 and period 2.

Furthermore, choice of different Budyko equations causes slight discrepancies in the attribution results (Wu et al., 2016). Besides, uncertainties in the meteorological and hydrological data would also influence the accuracy of the results to some extent.

This study indicated that the complementary method is a simple but effective tool to partition the effects of climate and catchment changes on the mean annual streamflow. These effects can also be estimated through model simulations (e.g. hydrological models and land surface models) under different scenarios, which could explain the impacts of climate variability, land use change, and other engineering measures on water resources in a more physical way. Comparing the results from complementary method with that from other methods may uncover underlying issues. Extending this method to other climatic regions may reveal interesting findings and improve understanding of

hydrologic response of climate change and human activities under different surface conditions.

6. Conclusion

In this study, a new attribution method (complementary method) proposed by Zhou et al. (2016) was first validated by comparison with the original sensitivity method (total differential method). Then, we attempted to apply this method to partition the contributions of climate change and human activities to the changes in annual streamflow in 22 catchments in China's Loess Plateau during the past three decades. The results revealed herein are helpful for developing adaptive measures in protecting water security. The main conclusions of our study are summarized as follows:

Observations of decreasing trends in streamflow were obvious across the plateau, with an overall average of -1.0 mm yr^{-2} from 1980 to 2009. After the GFG project, the annual streamflow decreased by 36% on average, with more intense reductions in northern catchments. In addition, parameter n, which indicated the sensitivity of streamflow to changes in climatic conditions, differed greatly at the individual catchment level, suggesting high spatial variability of the environmental conditions of the Loess Plateau.

When α varied from 0 to 1, we found that the average range of impacts of human activities on the annual streamflow from the complementary method was lower than that from the total differential method (2 ± 2.1 mm yr^{-1} versus 8.2 ± 13.6 mm yr^{-1}). Further, this human effect at half of the stations was underestimated or overestimated by the total differential method ($\alpha = 0.5$).

From period 1 (1980–1999) to period 2 (2000–2009), the contribution analysis from the complementary method showed that human-induced afforestation decreased streamflow by 26% (or 54% as a relative value) on average, confirming the previous findings that the increased evapotranspiration induced by the large-scale ecological restoration projects was the primary driver of the observed decline in streamflow. However, potential evapotranspiration alone can decrease streamflow by 9% (42% as a relative value), highlighting the importance of increasing atmospheric moisture demand in the water cycle. We found that climate and human effects have strong spatiotemporal variability. For catchments located in the middle part of the plateau, these two effects were generally opposite throughout the entire study period, while the reduction in streamflow in the northern catchments was caused by both climate change and human activities during the recent decade.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.01.386.

Acknowledgement

This work was funded by the National Natural Science Foundation of China (41771118), the Key Research and Development Program of China (2016YFC0501601), Fundamental Research Funds for the Central Universities (GK201802004), and Natural Science Foundation of Shaanxi Province of China (2017JM4011). We thank Zhou Sha in Tsinghua University for helpful discussions on the manuscript. We also thank the Editor, Associate Editor, and two anonymous reviewers for constructive comments, which helped us to improve the manuscript substantially.

References

Ahn, K.H., Merwade, V., 2014. Quantifying the relative impact of climate and human activities on streamflow. J. Hydrol. 515, 257–266.
Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320, 1444–1449.
Bourgault, M.A., Larocque, M., Roy, M., 2014. Simulation of aquifer-peatland-river interactions under climate change. Hydrol. Res. 45, 425–440.
Budyko, M., 1974. In: Miller, D.H. (Ed.), Climate and Life, Translated from Russian. Academic, San Diego by.
Choudhury, B., 1999. Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model. J. Hydrol. 216, 99–110.
Claessens, L., Hopkinson, C., Rastetter, E., Vallino, J., 2006. Effect of historical changes in land use and climate on the water budget of an urbanizing watershed. Water Resour. Res. 42, 446–455.
Donohue, R.J., Roderick, M.L., McVicar, T.R., 2012. Roots, storms and soil pores: incorporating key ecohydrological processes into Budyko's hydrological model. J. Hydrol. 436-437, 35–50.
Faramarzi, M., Abbaspour, K.C., Vaghefi, S.A., Farzaneh, M.R., Zehnder, A.J.B., Srinivasan, R., Yang, H., 2013. Modeling impacts of climate change on freshwater availability in Africa. J. Hydrol. 480, 85–101.
Farley, K.A., Jobbágy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Glob. Chang. Biol. 11, 1565–1576.
Feng, X.M., Sun, G., Fu, B.J., Su, C.H., Liu, Y., Lamparski, H., 2012. Regional effects of vegetation restoration on water yield across the Loess Plateau, China. Hydrol. Earth Syst. Sci. 16, 2617–2628.
Fu, B., 1981. On the calculation of the evaporation from land surface. Scientia Atmospherica Sinica 5, 23–31 (in Chinese).
Gao, P., Mu, X.M., Wang, F., Li, R., 2011. Changes in streamflow and sediment discharge and the response to human activities in the middle reaches of the Yellow River. Hydrol. Earth Syst. Sci. 15, 1–10.
Gao, G., Fu, B., Sivapalan, M., 2017. Spatio-temporal patterns of the effects of precipitation variability and land use/cover changes on long-term changes in sediment yield in the Loess Plateau, China. Hydrol. Earth Syst. Sci. 21, 4363–4378.
Graf, W.L., 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resour. Res. 35, 1305–1311.
Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111, 3251–3256.
Hovenga, P.A., Wang, D., Medeiros, S.C., Hagen, S.C., Alizad, K., 2016. The response of runoff and sediment loading in the Apalachicola River, Florida to climate and land use land cover change. Earth's Future 4, 124–142.
Huntington, T.G., 2006. Evidence for intensification of the global water cycle: review and synthesis. J. Hydrol. 319, 83–95.
Jackson, R.B., Carpenter, S.R., Dahm, C.N., Mcknight, D.M., Naiman, R.J., Postel, S.L., Running, S.W., 2001. Water in a changing world. Ecol. Appl. 11, 1027–1045.
Jiang, C., Xiong, L., Wang, D., Liu, P., Guo, S., Xu, C.-Y., 2015. Separating the impacts of climate change and human activities on runoff using the Budyko-type equations with time-varying parameters. J. Hydrol. 522, 326–338.
Li, L.J., Zhang, L., Wang, H., Wang, J., Yang, J.W., Jiang, D.J., Li, J.Y., Qin, D.Y., 2007. Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China. Hydrol. Process. 21, 3485–3491.
Li, Z., Liu, W.-z., Zhang, X.-c., Zheng, F.-l., 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. J. Hydrol. 377, 35–42.
Li, Y., Zhao, M., Motesharrei, S., Mu, Q., Kalnay, E., Li, S., 2015. Local cooling and warming effects of forests based on satellite observations. Nat. Commun. 6, 6603.
Li, S., Liang, W., Fu, B., Lü, Y., Fu, S., Wang, S., Su, H., 2016a. Vegetation changes in recent large-scale ecological restoration projects and subsequent impact on water resources in China's Loess Plateau. Sci. Total Environ. 569-570, 1032–1039.
Li, S., Liang, W., Zhang, W., Liu, Q., 2016b. Response of soil moisture to hydrometeorological variables under different precipitation gradients in the Yellow River Basin. Water Resour. Manag. 30, 1867–1884.
Li, J., Liu, D., Wang, T., Li, Y., Wang, S., Yang, Y., Wang, X., Guo, H., Peng, S., Ding, J., Shen, M., Wang, L., 2017. Grassland restoration reduces water yield in the headstream region of Yangtze River. Sci. Rep. 7, 2162.
Liang, W., Bai, D., Jin, Z., You, Y., Li, J., Yang, Y., 2015a. A study on the streamflow change and its relationship with climate change and ecological restoration measures in a sediment concentrated region in the Loess Plateau, China. Water Resour. Manag. 29, 4045–4060.
Liang, W., Bai, D., Wang, F., Fu, B., Yan, J., Wang, S., Yang, Y., Long, D., Feng, M., 2015b. Quantifying the impacts of climate change and ecological restoration on streamflow changes based on a Budyko hydrological model in China's Loess Plateau. Water Resour. Res. 51, 6500–6519.
Liu, Q., Mcvicar, T.R., 2012. Assessing climate change induced modification of Penman potential evaporation and runoff sensitivity in a large water-limited basin. J. Hydrol. 464-465, 352–362.
Liu, J., Li, S., Ouyang, Z., Tam, C., Chen, X., 2008. Ecological and socioeconomic effects of China's policies for ecosystem services. Proc. Natl. Acad. Sci. 105, 9477–9482.
Lü, Y., Fu, B., Feng, X., Zeng, Y., Liu, Y., Chang, R., Sun, G., Wu, B., 2012. A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. PLoS One 7, e31782.
McVicar, T.R., Van Niel, T.G., Li, L., Hutchinson, M.F., Mu, X., Liu, Z., 2007. Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. J. Hydrol. 338, 196–220.
Merritt, W.S., Alila, Y., Barton, M., Taylor, B., Cohen, S., Neilsen, D., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. J. Hydrol. 326, 79–108.
Mezentsev, V., 1955. More on the calculation of average total evaporation. Meteorol. Gidrol. 5.
Milly, P.C.D., 1994. Climate, soil water storage, and the average annual water balance. Water Resour. Res. 30, 2143–2156.
Ning, T., Li, Z., Liu, W., 2017. Vegetation dynamics and climate seasonality jointly control the interannual catchment water balance in the Loess Plateau under the Budyko framework. Hydrol. Earth Syst. Sci. 21, 1–25.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the World's forests. Science 333, 988–993.

Patterson, L.A., Lutz, B., Doyle, M.W., 2013. Climate and direct human contributions to changes in mean annual streamflow in the South Atlantic, USA. Water Resour. Res. 49, 7278–7291.

Penman, H.L., 1948. Natural evaporation from open water, hare soil and grass. Proc. R. Soc. Lond. 193, 120–145.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., Fang, J., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467, 43–51.

Prescott, J., 1940. Evaporation from a water surface in relation to solar radiation. Trans. R. Soc. South Aust. 64, 114–118.

Roderick, M.L., Farquhar, G.D., 2011. A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties. Water Resour. Res. 47, W00G07.

Sivapalan, M., Blöschl, G., Zhang, L., Vertessy, R., 2003. Downward approach to hydrological prediction. Hydrol. Process. 17, 2101–2111.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., IPCC, 2013. Climate change 2013: the Physical Science Basis. Cambridge University, Cambridge.

Tang, Y., Tang, Q., Tian, F., Zhang, Z., Liu, G., 2013. Responses of natural runoff to recent climatic variations in the Yellow River basin, China. Hydrol. Earth Syst. Sci. 17, 4471–4480.

Tomer, M.D., Schilling, K.E., 2009. A simple approach to distinguish land-use and climate-change effects on watershed hydrology. J. Hydrol. 376, 24–33.

Wang, D., Alimohammadi, N., 2012. Responses of annual runoff, evaporation, and storage change to climate variability at the watershed scale. Water Resour. Res. 48, W05546.

Wang, Y., Shao, M.A., Zhu, Y., Liu, Z., 2011. Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. Agric. For. Meteorol. 151, 437–448.

Wang, W., Shao, Q., Peng, S., Xing, W., Yang, T., Luo, Y., Yong, B., Xu, J., 2012. Reference evapotranspiration change and the causes across the Yellow River Basin during 1957–2008 and their spatial and seasonal differences. Water Resour. Res. 48, 113–122.

Wang, W., Shao, Q., Yang, T., Peng, S., Xing, W., Sun, F., Luo, Y., 2013. Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. Hydrol. Process. 27, 1158–1174.

Weiskel, P.K., Vogel, R.M., Steeves, P.A., Zarriello, P.J., Desimone, L.A., Ries, K.G., 2007. Water use regimes: characterizing direct human interaction with hydrologic systems. Water Resour. Res. 43, W04402.

Wu, J., Miao, C., Wang, Y., Duan, Q., Zhang, X., 2016. Contribution analysis of the long-term changes in seasonal runoff on the Loess Plateau, China, using eight Budyko-based methods. J. Hydrol. 545, 263–275.

Xiao, J., 2014. Satellite evidence for significant biophysical consequences of the "Grain for Green" program on the Loess Plateau in China. J. Geophys. Res. Biogeosci. 119, 2261–2275.

Xu, J., 2011. Variation in annual runoff of the Wudinghe River as influenced by climate change and human activity. Quat. Int. 244, 230–237.

Yan, D., Beurs, K.M.D., Fan, J., 2013. The impacts of weather and conservation programs on vegetation dynamics in China's Loess Plateau. Land 2, 573–594.

Yang, H., Yang, D., Lei, Z., Sun, F., 2008. New analytical derivation of the mean annual water-energy balance equation. Water Resour. Res. 44, W03410.

Yang, H., Qi, J., Xu, X., Yang, D., Lv, H., 2014a. The regional variation in climate elasticity and climate contribution to runoff across China. J. Hydrol. 517, 607–616.

Yang, H., Yang, D., Hu, Q., 2014b. An error analysis of the Budyko hypothesis for assessing the contribution of climate change to runoff. Water Resour. Res. 50, 9620–9629.

Zhan, C.S., Jiang, S.S., Sun, F.B., Jia, Y.W., Yue, W.F., Niu, C.W., 2014. Quantitative contribution of climate change and human activities to runoff changes in the Wei River basin, China. Hydrol. Earth Syst. Sci. 18, 3069–3077.

Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res. 37, 701–708.

Zhang, X.P., Zhang, L., Zhao, J., Rustomji, P., Hairsine, P., 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. Water Resour. Res. 44, W00A07.

Zhang, S.L., Yang, Y.T., McVicar, T.R., Yang, D.W., 2018. An analytical solution for the impact of vegetation changes on hydrological partitioning within the Budyko Framework. Water Resour. Res. 54, 519–537.

Zhao, G., Tian, P., Mu, X., Jiao, J., Wang, F., Gao, P., 2014. Quantifying the impact of climate variability and human activities on streamflow in the middle reaches of the Yellow River basin, China. J. Hydrol. 519, 387–398.

Zhao, G., Mu, X., Jiao, J., An, Z., Klik, A., Wang, F., Jiao, F., Yue, X., Gao, P., Sun, W., 2017. Evidence and causes of spatiotemporal changes in runoff and sediment yield on the Chinese Loess Plateau. Land Degrad. Dev. 28, 579–590.

Zhou, S., Yu, B., Huang, Y., Wang, G., 2015. The complementary relationship and generation of the Budyko functions. Geophys. Res. Lett. 42, 1781–1790.

Zhou, S., Yu, B., Zhang, L., Huang, Y., Pan, M., Wang, G., 2016. A new method to partition climate and catchment effect on the mean annual runoff based on the Budyko complementary relationship. Water Resour. Res. 52, 7163–7177.

Ziervogel, G., Johnston, P., Matthew, M., Mukheibir, P., 2010. Using climate information for supporting climate change adaptation in water resource management in South Africa. Clim. Chang. 103, 537–554.